Nitrous oxide emissions from an apple orchard soil in the semiarid Loess Plateau of China

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Abstract Nitrous oxide (N_2O) fluxes from an apple orchard soil in the semiarid Loess Plateau of China were measured using static chambers from September 2007 to September 2008. In this study, three sites were selected at distance of 2.5 m (D 2.5), 1.5 m (D 1.5), and 0.5 m (D 0.5) from the apple tree row. Nitrous oxide fluxes followed seasonal pattern, with high N_2O emission rates occurring in the hot-humid summer and low rates in the cold-dry winter. Pulses of N_2O emissions occurred after nitrogen fertilizer application, summer rainfall events, and during freeze-thaw cycles. Annual average N_2O emission rates were the highest at D 0.5 site ($48.2 \pm 39.9 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$), the lowest at D 2.5 site ($31.9 \pm 18.2 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$), and intermediate at D1.5 site ($36.8 \pm 32.2 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$), suggesting that N_2O emissions from the apple orchard soil increased when the chamber location was closer to the apple tree row. This may be due to the fertilization close to roots in hot and humid season. Over one third (37.1%) of the annual N_2O emission occurred in the summer. Annual N_2O emissions from the apple orchard soil averaged to $3.22 \text{ kg N}_2\text{O ha}^{-1} \text{ year}^{-1}$. Annual emission factor of the apple orchard from the applied fertilizer (uncorrected for background emission) was 0.658%. This value was nearly a half (53%) of the default value provided by the Intergovernmental Panel on Climate

Change for the application of synthetic fertilizers to cropland (1.25%). Therefore, the amount of N_2O emissions from the semiarid apple orchard soil could be largely over-estimated if no regional-specific factor is used.

Keywords Nitrous oxide emission · Apple orchard soil · Nitrogen fertilizer · Emission factor · China · Loess Plateau

Introduction

Nitrous oxide (N_2O) is a relatively stable greenhouse gas that also contributes to ozone layer destruction in the stratosphere. Agricultural soils are known to be responsible for a large proportion (70–81%) of the increase in N_2O emissions to the atmosphere, mainly due to the use of nitrogen fertilizer (Mosier et al. 1996; Dobbie et al. 1999; Weitz et al. 2001; Dobbie and Smith 2003; Stehfest and Bouwman 2006; Barton et al. 2007). Despite an increase in the number of N_2O measurements from agricultural soils in recent years, there is still a great deal of uncertainty in the current estimates of the total global N_2O emission, and the average 95% confidence interval for calculating N_2O emission was –51% to +107% (Stehfest and Bouwman 2006). Semiarid and arid lands constitute a large part of the global land area and are widely used for agricultural production. So far, the magnitude of the contribution of rain-fed semiarid agricultural soils to the global sources of N_2O is based only on the contribution by Barton et al. (2007) who measured N_2O in south-western Australia, reporting an annual N_2O emissions from 0.09 to 0.11 kg ha^{-1} and the emission factor of 0.02%, which was 60 times lower than the Intergovernmental Panel on Climate Change (IPCC) default value (Barton et al. 2007). In China, 43.1% of the land area is located in semiarid or arid climatic zones

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Fig. 1 Daily mean air temperature and precipitation in Changwu Agri-ecological Station, Loess Plateau of China

and is extensively used for agricultural production, but N_2O emissions from these croplands are not available (Zheng et al. 2004; Lu et al. 2006).

The Loess Plateau, which covers nearly $4.30 \times 10^5 \text{ km}^2$ in northwest China, is characterized by arid conditions and high soil erosion. The mean temperature and annual precipitation are in ranges of $3.6\text{--}14.3^\circ\text{C}$ and $150\text{--}750 \text{ mm}$, respectively. In order to reduce soil erosion and increase farmer income, apple orchards were established on a large area ($34^\circ\text{--}37^\circ\text{N}$) since the 1970s (Wu et al. 2008). Apple orchards cover an area of approximately 4.69% of the cultivated area in the Loess Plateau (about $7.83 \times 10^5 \text{ ha}$) and account for more than 62.0% of agricultural land in the study area (Wangdong Gou watershed, Li personal communication).

Nitrous oxide is mainly produced in soil by nitrification and denitrification, which are particularly controlled by soil water-filled pore space (WFPS), soil temperature, availability of labile organic carbon, soil pH, and the proportion and amount of ammonium and nitrate present (Bouwman 1998; Davidson et al. 2000; Dobbie and Smith 2003; Martin et al. 2003). In the apple orchards, these factors are strongly controlled by fertilizer management, weed control practices, and the phenology of the apple trees, which all had large

impacts on N dynamics in the apple orchard soils (Hoagland et al. 2008). In addition, compared with the cropland in this region, the apple orchards are always fertilized more than one time at high rates in different sites. The estimation of N_2O emission from apple orchard soil is needed to calculate the annual emission of N_2O in the Loess Plateau region.

The objectives of this study were therefore to determine the temporal variations of N_2O fluxes from an apple orchard soil in the Loess Plateau and to investigate its relationship to soil and environmental factors, such as air temperature, soil moisture, and fertilization.

Materials and methods

Experimental site and soils

The study was conducted at the Changwu Agri-ecological Station, Loess Plateau ($107^\circ 41'\text{E}$, $35^\circ 14'\text{N}$, 1,200 m above sea level) in Changwu County, Shaanxi Province, China. The investigated area is representative of the gully terrain in the Loess Plateau, and the climate is classified as semiarid, with annual average precipitation of 565 mm, of which nearly 49% occurs from July to September. The annual mean temperature (1984–2004) is 9.1°C , and there are about 171 frost-free days each year (Fig. 1). The soil is a coarse-textured dark loessial soil. The main characteristics of the soil at the depth of 0–40 cm are: soil organic carbon $4.05\text{--}6.55 \text{ g kg}^{-1}$, total nitrogen $0.86\text{--}1.09 \text{ g kg}^{-1}$, available phosphorus 3.0 mg kg^{-1} , pH 7.87–8.55, bulk density $1.19\text{--}1.30 \text{ g cm}^{-3}$, mineral nitrogen $1.39\text{--}1,114 \mu\text{g g}^{-1}$, and clay content 24% ($<0.002 \text{ mm}$; Table 1).

Experimental design

The apple orchard (which was converted from the former winter wheat field in 1984) was dominated by Fuji apple trees

Table 1 The main physiochemical characteristics of soil

Parameters	Soil layer (cm)	Measuring sites		
		D 2.5	D 1.5	D 0.5
Soil organic carbon (g kg^{-1})	0–10	6.55 ± 0.14	6.00 ± 0.09	6.22 ± 0.94
	10–20	4.72 ± 0.59	4.95 ± 0.08	4.42 ± 0.20
	20–40	4.05 ± 0.10	5.19 ± 0.20	5.28 ± 1.12
Total nitrogen (g kg^{-1})	0–10	1.01 ± 0.02	1.02 ± 0.02	1.05 ± 0.01
	10–20	0.89 ± 0.01	1.04 ± 0.03	0.89 ± 0.01
	20–40	0.91 ± 0.05	1.09 ± 0.04	0.86 ± 0.02
pH (H_2O)	0–10	8.49 ± 0.02	8.19 ± 0.01	8.30 ± 0.01
	10–20	8.55 ± 0.01	8.00 ± 0.03	8.17 ± 0.01
	20–40	8.48 ± 0.02	7.87 ± 0.00	8.08 ± 0.01
Bulk density (g cm^{-3})	0–30	1.30 ± 0.06	1.19 ± 0.06	1.22 ± 0.04

The soil parameters were given by mean $\pm$ standard deviations of five soil samples collected in June 2008 according to standard methods. The D 2.5, D 1.5, and D 0.5 were the measuring sites 2.5, 1.5, and 0.5 m from apple tree row, respectively

(*Malus pumila* Mill). The plant density is 1,020 plants ha⁻¹, and the distance between the two rows of apple trees was 5 m. The size of the crown of each apple tree was about 3.5 m. Thinning occurred during April and May. The apple orchards in this area are not irrigated, and rainfall is the only source of water. The apple orchard was fertilized twice at a soil depth of ~25 cm by digging a hole at 1.5 m from tree row in late March (235 kg N ha⁻¹ as urea) and in late June (76.5 kg N ha⁻¹ as compound fertilizer) with the hole at 0.5 m from tree row. In July, weeds were manually hoed up. Several local-produced pesticides and fungicides were foliar sprayed two or three times per year to prevent pests and diseases. Annual amounts of active constituents applied were 3 kg ha⁻¹ of propineb, 2.2 kg ha⁻¹ of thiophanate-methyl, 0.5 kg ha⁻¹ of methomyl, 1.8 kg ha⁻¹ of polyoxin, and 0.4 kg ha⁻¹ of hexaconazole, respectively. Nitrous oxide emissions were measured by closed chamber methods at: 2.5 m (hereafter, referred to as D 2.5), 1.5 m (D 1.5), and 0.5 m (D 0.5) from the rows of trees. Site D 2.5 was in the middle of the two rows of the apple trees. For each site, three replicate chambers were used. The three sampling sites were selected to investigate the effect of the fertilizer application and the apple tree on N₂O emission.

Flux measurements

Nitrous oxide emissions were measured from September 2007 to September 2008 at biweekly intervals except immediately after each fertilizer application and during the freezing and thawing cycles when more measurements were conducted. From January 3 to February 21, 2008 emissions were not measured due to very heavy snow. During this period, conditions were generally not favorable for N₂O production as the soil temperature was below -1°C. Measurements were carried out using static chambers in the midmorning (between 8AM and 12AM). The chambers (50 × 50 × 50 cm) were of transparent PVC fixed to aluminum alloy frames. A buffer pipe (1.5 m, 0.6 mm o.d. (outer diameter), 0.4 mm i.d. (inner diameter)) was inserted through the lid to keep the air pressure balanced between the inside and the outside of the chamber. A fan (12 V, 0.5 A), 8 cm in diameter, was installed on the top wall of each chamber to mix the air when chamber was closed. Permanently positioned chamber bases (length × width × height = 50 × 50 × 5 cm) with water-filled grooves in the upper end were used to ensure gas tightness. During the flux measurements, gas within the chamber was sampled into 0.5 L polyethylene-coated aluminum bags using a membrane pump at 0, 9, 18, and 27 min after the set of the chamber. Nitrous oxide concentrations of samples were analyzed by gas chromatography (Model SP3410, Beijing Analytical Instrument Factory) with an electron capture detector (ECD). The gas samples were loaded into a 2 ml loop connected to a

10-port valve. Both a precolumn (2 m, 4 mm, o.d.) and an analytical column (2 m, 4 mm, o.d.) were packed with Porapak Q, 80–100 mesh and hold at 72°C. Pure nitrogen was used as carrier gas with a flow rate of 30 ml min⁻¹. The temperature values of the ECD and injection port were 390 and 72°C, respectively. A small amount of CO₂ (6 ml min⁻¹) was added into makeup gas of ECD so as to improve the sensitivity and repeatability of ECD. Analytical variability was less than 1%. Nitrous oxide flux was calculated by the rate of the change in the N₂O concentration in the chamber, estimated as the slope of linear regression between N₂O concentration and time. Flux rates were discarded if the regression coefficient (r^2) was less than 0.85.

Soil measurement and analysis

During each gas sampling, soil temperatures at 10 cm soil depth, soil moisture (0–30 cm), and the internal temperature of chambers were simultaneously monitored. The initial and final air temperatures in each chamber were recorded to calculate the fluxes. Soil temperatures were measured with a SN2202 digital thermo detector (Sinan Instrument Plant of Beijing Normal University; Qi et al. 2007). Soil moisture (0–30 cm) was determined gravimetrically after oven-drying (at 105°C for 24 h). During the measurements, bulk density was determined monthly, allowing soil WFPS to be calculated from the soil water content values (Merino et al. 2004). Climatic data (precipitation, air temperature, and atmospheric pressure) were obtained from Changwu Agri-ecological Station of the Loess Plateau located at 100 m from the experimental site.

At the different phenological stages of the orchard, soil samples at the depths of 0–10, 10–20, and 20–40 cm were taken at five sites near the chamber bases by a 5-cm-diameter gouge auger. The soil samples were placed in labeled airtight bags and brought to the lab, where they were sieved (2 mm). Soil mineral nitrogen (NO₃⁻ and NH₄⁺) was extracted with 0.01 M KCl and measured by colorimetric continuous flow analyzer (SANT++, Skalar Company, the Netherlands; Schlöter et al. 2003).

Statistical analysis

Cumulative N₂O emissions from each site were calculated by integrating weekly fluxes from the three replicates, assuming a constant flux rate between two gas sampling times. The N₂O flux was correlated with the measured variables. The relationships among soil and environmental factors, namely soil temperature (0–10 cm), air temperature, WFPS, and rainfall (in three preceding days) were analyzed by stepwise linear multiple regressions. Comparisons among the three sites were made using a one-way analysis

of variance. All these statistical analysis were performed by SPSS 13.0 (SPSS Inc., USA). Annual N_2O emission from this apple orchard soil was estimated from an area after weighting the emission of three sites.

Results

Soil temperature in the top 10 cm exhibited a clear seasonal pattern (Fig. 2a). The highest soil temperatures were 27.4, 24.3, and 24.1°C at D 2.5, D 1.5, and D 0.5 sites, respectively, and occurred on June 27, 2008. Soil temperature decreased gradually from 23°C in September to below 0°C on December 10, 2007. On February 22, 2008, in early spring, soil temperature rose with time.

Soil WFPS over the top 30 cm soil varied widely in response to rainfall and the growth of the apple trees (Fig. 2b). Generally, the WFPS of the D 2.5 site was higher than the other two sites. At both D 0.5 and D 2.5 sites, the highest WFPS (66.2% and 70.8%, respectively) occurred during the freeze-thaw cycles (from February 22 to March 13, 2008). In both sites, WFPS exceed 60.0% immediately after a heavy rainfall. At D 1.5 site, WFPS exceeded 60.0% only immediately after a heavy rainfall.

Soil NH_4^+ and NO_3^- concentrations in the top 40 cm of the soil varied widely during the different phenological stages of the orchard at the D 1.5 and D 0.5 sites where fertilizer was applied, whereas, remained relatively constant at the D 2.5 site (Table 2). From April 16 to June 27 2008, soil NH_4^+ and NO_3^- concentrations of the D 2.5 site were much lower than in the other two sites. During this period, the higher soil NH_4^+ and NO_3^- concentrations were at all soil depths at D 0.5 site, and this coincided with the active growing phase of the trees. At the D 1.5 site, soil NH_4^+ concentrations in the 10–20 cm of soil were generally greater than the concentrations at 0–10 and 20–40 cm depth, and soil NO_3^- concentrations generally increased by increasing soil depth.

Nitrous oxide fluxes varied widely in space and time and were stimulated by nitrogen fertilizer application (Fig. 2c). There was a sharp increase in N_2O emissions at the D 0.5 site after the application of fertilizer on June 24, 2008. The highest emission, $170 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$, occurred 8 days after fertilizer application. In contrast, there was only a small increase in the N_2O fluxes after applying the urea on March 28, 2008 at the D 1.5 site, with the highest emissions being $73.8 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$ 7 days after fertilizer application. During freeze-thaw cycles, N_2O emissions increased in all three sites, with the peak values being 109, 60.6, and $50.9 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$, respectively. At the D 1.5 site, N_2O fluxes were high in summer 2008 (from June 6 to August 9, 2008), with the maximum value being $177 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$. During the early period of the apple

tree defoliation (September 17, 2007), N_2O emissions were also higher at the D 0.5 and D 1.5 sites than at D 2.5 site. The N_2O emissions at the D 2.5 site were high from June 6 to August 24, 2008 and during the freeze-thaw period (from February 22 to March 13, 2008), accounting for 34.7% and 8.61% of the annual emissions, respectively.

Annual average N_2O emission rates were highest at the D 0.5 site ($48.2 \pm 39.9 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$), lowest at D 2.5 site ($31.9 \pm 18.2 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$), and intermediate at D 1.5 site ($36.8 \pm 32.2 \mu\text{g N}_2\text{O m}^{-2} \text{h}^{-1}$; Fig. 3). There was a significant difference in the annual average N_2O emission rates between D 0.5 site and D 2.5 site ($P \leq 0.05$; Fig. 3). As described above, the annual N_2O emission from this apple orchard soil was estimated from an area by weighting emission at the three sites, and it was $3.22 \text{ kg N}_2\text{O ha}^{-1} \text{ year}^{-1}$. The annual emission factor from the apple orchard soil, uncorrected for background emission, was 0.658%.

The N_2O fluxes were significantly correlated with soil temperature and ambient air temperature at D 0.5 and D 1.5 sites ($P \leq 0.05$ and $P \leq 0.01$, respectively). At the D 2.5 site, there was only significant correlation between N_2O fluxes and ambient air temperature ($P \leq 0.05$). There was no significant correlation between N_2O fluxes and WFPS. There was a significant correlation between the N_2O flux and concentrations of soil NO_3^- at the 20–0 cm depth at the D 0.5 site ($P \leq 0.01$). The multiple regression of N_2O flux with soil temperature at 0–10 cm, air temperature, WFPS, and accumulated rainfall in three antecedent days showed that air temperature could be identified as the only key factor determining the temporal variability of N_2O flux at each sites and accounted for 19%, 24%, and 20% of the temporal variation in sites D 2.5 ($P < 0.1$), D 1.5 ($P < 0.002$), and D 0.5 ($P < 0.006$), respectively.

Discussion

The fluxes of N_2O from terrestrial ecosystem are more uncertain than that of other greenhouse gases (such as CO_2 and CH_4). The coefficients of variations (CVs) of N_2O emission for the three replicates were 0.27, 0.23, and 0.25 at sites D 2.5, D 1.5, and D 0.5, respectively. The seasonal CVs were in ranges of 3–66%, 1–53%, and 3–61% at sites D 2.5, D 1.5, and D 0.5, respectively.

Soil WFPS at all sites was always below 60.0% except during freeze-thaw cycle and immediately after heavy rainfall. The coarse texture and the low water retention capacity of soils limited the possibility of the formation of anaerobic microsites, where N_2O production could take place (Castaldi et al. 2004). Nitrous oxide emission is affected by soil moisture (Ciarlo et al. 2008), and indeed higher N_2O emission occurred after raining in this study. Previous studies have indicated that denitrification rates

Fig. 2 Soil temperature (0–10 cm; **a**), WFPS (0–30 cm; **b**), and N_2O fluxes during the study period in the apple orchard. Arrows indicate the timing of fertilizer application (**c**)

increased rapidly when WFPS exceeds 63%, whereas nitrification was the dominant source of N_2O when the WFPS was in the range of 30–70% (Davidson et al. 2000; Ciarlo et al. 2008; Zhang and Han 2008). Therefore, it seems reasonable to hypothesize that nitrification is the main source of N_2O in this region. The study area showed a clear seasonal pattern in air temperature and soil temperature, and N_2O emissions from the three sites were significantly correlated with the air temperature. Dong et al. (2001) also found that there was a significant correlation

between N_2O fluxes and ambient air temperature in their cultivated soils of the North China Plain.

The urea applied in soil is hydrolyzed to NH_4^+ , which is the substrate for nitrification, so that N_2O fluxes can increase after urea fertilization (Barton et al. 2007). However, N_2O fluxes varied widely in response to the two N fertilizer application and were usually greater after the fertilization in June than after the fertilization in March because in late June, the soil conditions were more conducive for N_2O production than during the late March

Table 2 Soil nitrate and ammonium content during the different phenological stages of the apple orchard

Site	Concentration ($\mu\text{g g}^{-1}$)	Soil depth (cm)	Sampling date					
			26/10/2007	04/03/2008	16/04/2008	09/05/2008	28/06/2008	01/08/2008
D 2.5	NH_4^+	0–10	7.78 $\pm$ 0.650	4.82 $\pm$ 0.0625	25.4 $\pm$ 1.27	20.0 $\pm$ 3.42	3.24 $\pm$ 0.382	3.00 $\pm$ 0.458
		10–20	4.20 $\pm$ 0.688	2.39 $\pm$ 0.0462	50.9 $\pm$ 3.26	10.6 $\pm$ 1.21	2.65 $\pm$ 0.259	3.17 $\pm$ 0.263
		20–40	4.60 $\pm$ 0.625	4.86 $\pm$ 0.625	16.7 $\pm$ 2.35	11.3 $\pm$ 1.67	2.36 $\pm$ 0.0630	3.46 $\pm$ 0.925
	NO_3^-	0–10	15.1 $\pm$ 15.1	12.1 $\pm$ 0.750	4.55 $\pm$ 2.09	22.6 $\pm$ 1.39	16.7 $\pm$ 1.02	3.14 $\pm$ 0.915
		10–20	34.5 $\pm$ 26.6	11.6 $\pm$ 6.44	5.16 $\pm$ 3.11	9.55 $\pm$ 1.76	8.10 $\pm$ 0.582	1.68 $\pm$ 0.922
		20–40	46.9 $\pm$ 23.5	15.7 $\pm$ 0.813	3.26 $\pm$ 0.876	8.20 $\pm$ 3.47	7.71 $\pm$ 4.85	4.44 $\pm$ 0.198
D 1.5	NH_4^+	0–10	13.6 $\pm$ 11.7	4.69 $\pm$ 1.50	42.9 $\pm$ 4.79	323 $\pm$ 20.7	1.99 $\pm$ 0.438	3.54 $\pm$ 0.0686
		10–20	17.4 $\pm$ 13.1	3.98 $\pm$ 1.00	85.1 $\pm$ 6.27	487 $\pm$ 12.4	2.48 $\pm$ 0.319	3.76 $\pm$ 0.207
		20–40	12.6 $\pm$ 19.4	5.35 $\pm$ 0.313	11.4 $\pm$ 1.37	59.3 $\pm$ 10.2	2.07 $\pm$ 0.266	3.36 $\pm$ 0.461
	NO_3^-	0–10	38.2 $\pm$ 27.1	12.0 $\pm$ 3.69	3.46 $\pm$ 0.249	147 $\pm$ 24.7	15.6 $\pm$ 7.94	9.36 $\pm$ 1.30
		10–20	69.4 $\pm$ 12.4	11.2 $\pm$ 1.25	3.67 $\pm$ 0.364	279 $\pm$ 43.0	69.1 $\pm$ 6.31	8.94 $\pm$ 0.621
		20–40	459 $\pm$ 14.0	52.2 $\pm$ 1.12	1.39 $\pm$ 0.247	375 $\pm$ 42.4	215 $\pm$ 5.12	33.5 $\pm$ 6.91
D 0.5	NH_4^+	0–10	10.1 $\pm$ 3.68	4.51 $\pm$ 0.875	48.4 $\pm$ 6.38	759 $\pm$ 2.39	120 $\pm$ 4.78	3.47 $\pm$ 0.140
		10–20	12.4 $\pm$ 8.17	3.40 $\pm$ 0.688	153 $\pm$ 9.24	1114 $\pm$ 79.8	229 $\pm$ 7.74	2.79 $\pm$ 0.300
		20–40	10.4 $\pm$ 6.31	3.93 $\pm$ 0.563	69.3 $\pm$ 4.45	639 $\pm$ 100	154 $\pm$ 13.2	2.74 $\pm$ 0.400
	NO_3^-	0–10	6.31 $\pm$ 0.736	9.15 $\pm$ 1.69	222 $\pm$ 31.5	36.5 $\pm$ 7.68	65.8 $\pm$ 9.19	4.32 $\pm$ 0.631
		10–20	18.7 $\pm$ 8.00	11.3 $\pm$ 0.813	66.0 $\pm$ 23.1	11.5 $\pm$ 1.92	89.5 $\pm$ 8.66	2.09 $\pm$ 0.329
		20–40	15.0 $\pm$ 1.48	9.68 $\pm$ 0.688	2.88 $\pm$ 0.855	9.83 $\pm$ 2.76	177 $\pm$ 8.38	2.88 $\pm$ 1.27

since soil temperature was generally higher than 20.0°C, and the top soil was subjected to regular wetting and drying cycles (Davidson et al. 1993; Dobbie et al. 1999; Du et al. 2006).

On June 8, 2008, we found that the greatest fluxes of N_2O at D 2.5 site occurred after the first summer rainfall of more than 10 mm (Fig. 2c). At both D 1.5 and D 0.5 sites, the greatest fluxes of N_2O occurred on the second day of the continuous rainfall probably because the effects of the rainfall on soil moisture differed among sites beneath the apple trees.

In temperate climates, freeze-thaw cycles can increase N_2O emission rates (Muller et al. 2002). In this study, the pulse of N_2O emission occurred in early spring (Fig. 2c), but it lasted shortly and contributed little to the annual emission. Probably there was no enough N_2O accumulation beneath the frozen soil layers as the conditions (no input of organic matter and N fertilizer during the winter to soil) were not conducive for N_2O production. On the other hand, during the middle and the late of the freeze-thaw cycles, the apple trees in the bud phase began to compete with soil microorganisms for available soil N (Groffman et al. 2006).

In this study, the proportion of the applied N fertilizer emitted as N_2O –N was 0.658% by including the contribution of the background emission and was about 1.90 times less than the default value provided by the IPCC (1997), 1.40 times less than the direct emission factor determined by Lu et al. (2006) for agricultural soils in China, and 32.9

times higher than the only available emission factor for the rain-fed agricultural soils in semiarid region reported by Barton et al. (2007). Although both studies have been conducted in agricultural soils in rain-fed semiarid regions, the climate patterns differed with those of our study, for example, our study site had an annual rainfall of 584 mm and was subjected to freeze-thaw cycles, whereas the site of Barton et al. (2007) has annual precipitation of 358 mm and was not subjected to freeze-thaw cycles. In addition both sites had different soil types, different crops, and different tillage and nitrogen fertilizer managements, and the emission factor reported by Barton et al. (2007) was

Fig. 3 Annual average N_2O emission rates during the study period at the three sites. Different letters indicate the significant difference ($P \leq 0.05$) in N_2O emission rates among the three sites

corrected for background emission. In order to obtain a robust mean emission factor for semiarid agriculture, multiyear and automated measurements at several typical sites are needed.

The extension of the apple orchard area in Loss Plateau of China is about 7.83×10^5 ha (including Shaanxi, Shanxi, Qinghai, Ningxia Gansu Provinces). The annual (377 days) N_2O emission from the apple orchards in this region was estimated to be 2.52×10^9 g N_2O , accounting for about 0.92% of the total N_2O emissions from Chinese croplands (Zheng et al. 2004). Assuming that the total area of apple orchards in China is 1.89×10^6 ha, we estimated an overall N_2O emission from the apple orchards of about 6.08×10^9 g N_2O , which accounted for about 2.21% of the total N_2O emissions from Chinese croplands (Zheng et al. 2004).

Conclusions

The year measurements of N_2O from an apple orchard soils in the semiarid Loess Plateau (China) indicated that the apple orchards are a potential source of N_2O emission with high N_2O emission rates in the hot-humid summer and low rates in the cold-dry winter. Pulses of N_2O emissions occurred after N fertilizer application, summer rainfall events, and during freeze-thaw cycle. These short-term pulses contributed significantly to the annual N_2O emission and should be captured during field measurements of N_2O emission. Multiple automated chambers system can provide a good approach for measuring N_2O with high temporal resolution and possibilities of having more replicates and under all meteorological conditions.

Over one third (37.1%) of the annual N_2O emission occurred in the summer, when soil temperature was generally higher than 20°C , with greater levels of available carbon and nitrogen and more frequent dry-wet-dry cycles; these conditions were favorable to N_2O production. The results of stepwise multiple linear regression showed that air temperature was the only key factor influencing the temporal variation in N_2O flux. Cumulative annual N_2O emissions from soil were estimated to be $3.22 \text{ kg } \text{N}_2\text{O } \text{ha}^{-1} \text{ year}^{-1}$, and the annual emission factor uncorrected for background emission was 0.658%. This work has confirmed the findings of Barton et al. (2007), that the proportion of N fertilizer lost from cropland in semiarid climates is likely much lower than the global average.

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